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Three Dimensional Field Calculations for a Short Superconducting Dipole for the UCLA Ultra Compact Synchrotron*

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Abstract--- The Ultra Compact Synchrotron (UCS), proposed for UCLA, is a compact 1.5 GeV electron light source with superconducting magnets to produce X rays with a critical energy of about 10 keV. The design physical length (cold length) for the dipole is 418 mm. The synchrotron requires that a uniform field be produced in a region that is 180 mm wide by 40 mm high by about 380 mm long. The end regions of the dipole should be short compared to the overall length of the dipole field region. A Vobly H type of dipole was selected for the synchrotron bending magnets. In order for each dipole to bend a 1.5 GeV electron beam 30 degrees, the central induction must be in the range of 6.4 to 6.9 T (depending on the dipole magnetic length). The pole width for the dipole was set so that over 90 percent of the X rays generated by the magnet can be extracted. The three dimensional field calculations were done using TOSCA. This report shows that a Vobly type of dipole will behave magnetically as a conventional water cooled iron dominated dipole. The uniformity of the integrated magnetic field can be controlled by varying the current in the shield coil with respect to the gap and cross-over coils. The two dimensional field in the center of the magnet can be tuned to be very uniform over a width of 110 to 120 mm. The three dimensional calculations show that the magnetic length along a particle track in the dipole is about 29 mm longer than the length of the iron pole pieces. This report will present the three dimensional design of the UCS Vobly dipole and the results of the field calculations for that magnet.

I. BACKGROUND

UCLA has proposed an Ultra Compact 1.5 GeV electron Synchrotron storage ring (UCS) to produce X rays with a critical energy in excess of 10 keV[1]. The circumference of the storage ring is about 27.4 meters. The machine is designed to fit in a shielded hall that is 9.14 m (30 feet) wide. The key to making this machine compact and at the same time being able to produce 10 keV X rays is the twelve superconducting bending magnets that bend the electrons and produce the high energy X rays. Raising the dipole induction allows one to reduce the machine energy for a given X ray critical energy and reduce the magnetic length of each dipole for a given storage ring energy. An electron storage ring with 1.2 T dipoles that produces X rays with a 10 keV critical energy, would have a machine energy of 3.6 GeV. A 3.6 GeV storage ring would have a minimum circumference of at least 120 m and would require a hall that is over 38 m wide.

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II. DIPOLE REQUIREMENTS FOR THE UCS RING

The superconducting dipoles for the UCS are defined by the storage ring[2]. These dipoles must have the following characteristics: 1) The physical length of the dipole is dictated by the beam bend radius. At 1.5 GeV, the beam bend radius is 714 mm at an induction of 7.00 T. The magnetic length of a 7 T dipole along the bent beam in a 30 degree bend dipole is 373.9 mm. The physical length of the iron in the UCS dipole is set at 380 mm. 2) The width of the cold pole is dictated by the width of a 15 sigma beam electron beam, the sagitta of the bent beam, the width of the fan for synchrotron radiation generated at the start of the dipole and an allowance for cryogenic insulation. The cold horizontal pole width for the UCS dipole is 180 mm. 3) The cold gap for the magnet is dictated by the vertical height of a 15 sigma beam and an allowance for cryogenic insulation. The UCS dipole vertical cold aperture is 40 mm. 4) As in conventional iron dominated dipoles, the magnetic length of the UCS dipole must be about the same as the length of the iron pole. 5) The magnetic field must be uniform to a few parts in 10000 over 75 percent of the horizontal aperture of the dipole. 6) The integrated field (the integral of the magnetic field from minus infinity to plus infinity as one goes in the direction of the beam) uniformity must be better than a one in 10000 over a region that is ± 20 mm from the beam center in the horizontal direction. The superconducting dipoles that have been previously used in accelerators such as HERA or the Fermilab Tevatron do not have the characteristics given above. Figures 1 shows the UCS dipole TOSCA model. Table 1 shows the design parameters of the UCS dipole.

TABLE I 1.5 GeV COMPACT LIGHT SOURCE
SUPERCONDUCTING DIPOLE PARAMETERS

Number of Dipoles	12
Dipole bend Angle (degrees)	30.0
X Ray Fan Angle (degrees)	~30.0
Required Integrated Induction*(T m)	2.620
Design Induction at Center* (T)	~6.504
Magnetic Length (mm)	~403
Magnet Cold Gap (mm)	40.0
Magnet Iron Pole Width (mm)	180.0
Iron Pole Length (mm)	376.0
Shield Coil Height (mm)	160.0
Coil Thickness (mm)	21.6
Stored Energy* (kJ)	~243
Peak Induction in Winding* (T)	~6.64
Iron Width (mm)	782.0
Iron Height (mm)	574.0
Estimated Cold Mass per Dipole (kg)	~1400

* for a 1.5 GeV electron beam

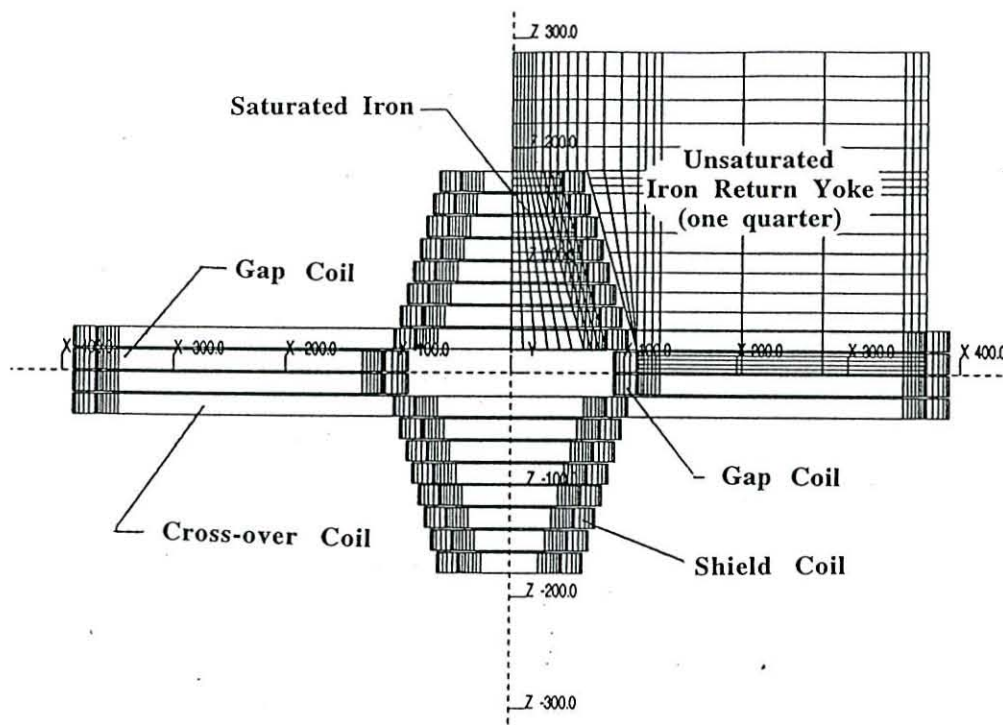


Figure 1 The TOSCA Coil and Iron Model for the UCS Dipole (The upper right hand corner shows the iron.)

III. THE UCS SUPERCONDUCTING DIPOLE DESIGN

Picture frame dipoles have the characteristics required for the UCS dipole as long as the iron in the pole and the flux return is unsaturated. The proposed dipole for the UCS is a modified picture frame dipole that has extra coils that keep the magnetic flux contained within the iron poles as they start to saturate. The UCS dipole design is based on a design developed by Pavel Vobly at INP Novosibirsk[3,4]. The Vobly type dipole can have saturated iron in the poles, but current in the shield coils keeps the magnetic flux in the pole until it can be returned by an unsaturated iron return yoke on the outside. As a result, the end field fall off is similar to that of conventional iron dominated dipoles. The crossover coils in the Vobly design serve two purposes: 1) They keep the magnetic length of the dipole close to the iron length. 2) The coils that generate the field in the gap do not have to cross over the ends of the magnet, which simplifies coil fabrication. The advantage of a meeting the requirements of the UCS dipoles with relatively simple coils far outweighs the extra cost of the superconductor.

Reference [5] presents some basic design equations for magnets of the Vobly type. This report explains how the iron dimensions are obtained based on knowing the cold horizontal width of the pole, the magnet cold gap, the design saturation induction for the iron, and the design induction in the magnet gap. The magnet design shown in Figure 1 is

based upon a saturation induction in the iron of 2.15 T when the central induction is 6 T. The design saturation induction was based on preliminary two dimensional calculation done a Vobly dipole in done in 1995. Ordinary 1010 steel was used for these calculations. At a central induction of 6.5 T, the return iron within the gap coils is saturated.

IV. THREE DIMENSIONAL FIELD CALCULATIONS OF THE UCS DIPOLE

The 1995 two dimensional calculations of the magnetic induction in a UCS dipole[6] show the following: 1) The design saturation induction of 2.15 T appears to be justified. When the central induction within the dipole bore drops to 2.15 T, the current in the shield coils is nearly zero. 2) One can control the two-dimensional field uniformity within the magnet gap by changing the shield coil current density with respect to the current density in the gap and cross-over coils. 3) The two-dimensional field uniformity within gap can be better than a few parts in 10000 over about 75 percent of the magnet gap width, provided the current density in the shield coils is at the proper value. The two-dimensional field calculations suggest that the integrated field quality can be controlled by varying the current in the shield coils provided the three-dimensional field falls off rapidly through the magnet ends. The three dimensional field calculations allow one to test various design concepts for the magnet.

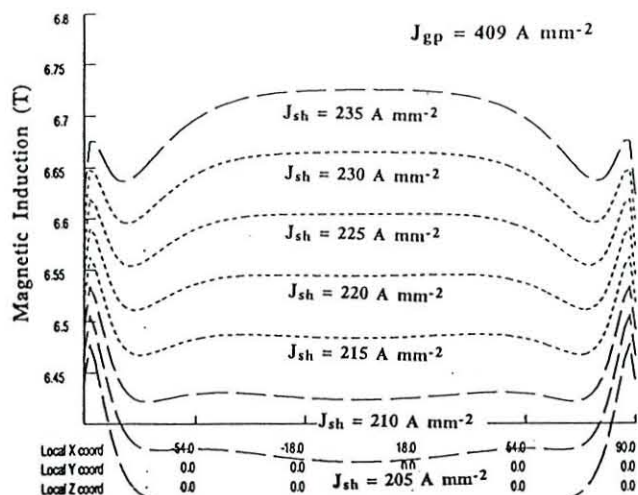


Fig. 2 Central Magnetic Induction across for Various Shield Coil Current Densities with $J_{gp} = 409 \text{ A mm}^{-2}$

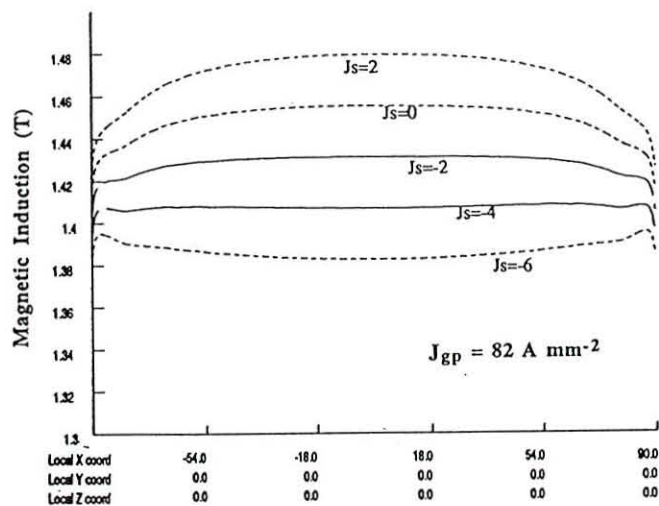


Fig. 3 Central Magnetic Induction across for Various Shield Coil Current Densities with $J_{gp} = 82 \text{ A mm}^{-2}$

TOSCA was used to do the three-dimensional field calculations were done on the UCS dipole shown in Figure 1. The magnet modeled has an iron pole length of 376 mm, a cold pole gap is 40 mm and a cold pole width is 180 mm. A reduced gap between poles should reduce the end effects in the magnet, while the increased pole width will ensure that the good field region across the pole will be wider.

The three dimensional field calculations were done at two levels of magnet current excitation. The upper level of excitation represents a level that is close to the induction needed to bend the beam when the ring energy is 1.50 GeV. The lower level of excitation represents a case where the current density in the gap and cross-over coils is reduced by a factor of five, a case that is close to the probable injection

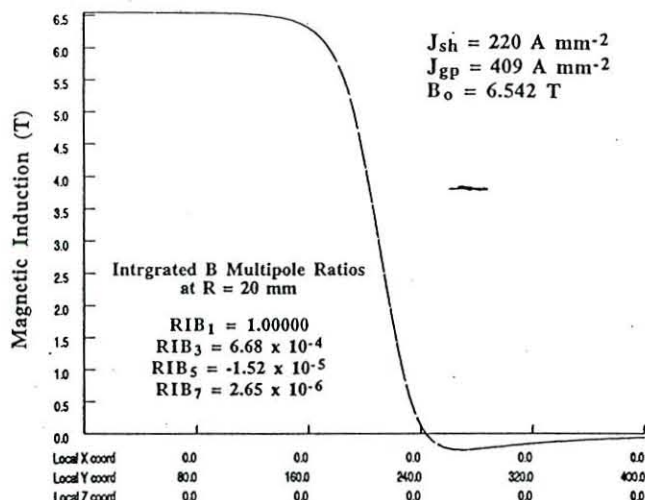


Fig. 4. B from the Magnet Center ($y = 0$) to $y = 400 \text{ mm}$ over $60 \text{ mm} \times \text{span around } x = 0$, $B_0 = 6.542 \text{ T}$

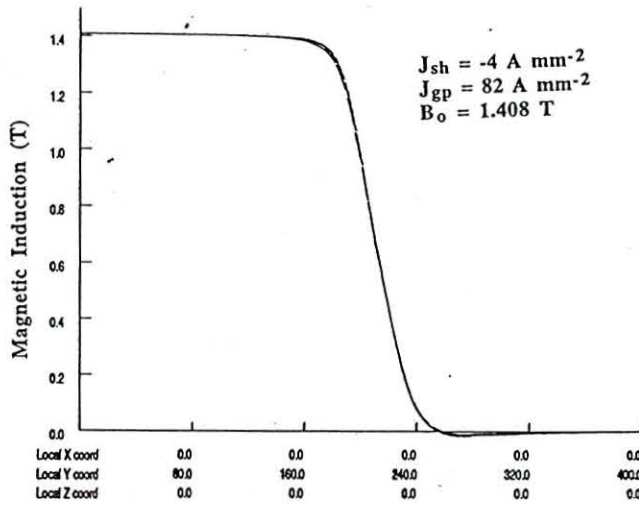


Fig. 4. B from the Magnet Center ($y = 0$) to $y = 400 \text{ mm}$ over $60 \text{ mm} \times \text{span around } x = 0$, $B_0 = 1.408 \text{ T}$

energy for the ring at 300 MeV. The central induction at the center of the magnet when the field is most uniform is about 6.542 T at the upper level of excitation. At the lower level of excitation, the central induction at most uniform field current in the shield coil is 1.408 T. The central in induction at the lower level of excitation is not a factor of five lower than the induction at the higher level of excitation. Saturation in the poles and the iron return yoke accounts for the difference in the induction at the higher level of excitation.

Figure 2 shows the magnetic induction across the pole along a line at the midplane across the middle of the magnet, when the current density in the gap and crossover coils is 409 A mm^{-2} . The curves in Figure 2 represent various shield coil

current densities in the shield coils ranging from 200 A mm⁻² to 235 A mm⁻². It appears that the most uniform field across the middle of the three dimensional magnet occurs when the current density in the shield coil is around 220 A mm⁻². Figure 3 shows the magnetic induction across the pole along a line at the midplane across the middle of the magnet, when the current density in the gap and crossover coils is 82 A mm⁻². The most uniform field in this case occurs when the excitation in the shield coils is -4 A mm⁻².

Figure 4 shows the magnetic induction from the center of the magnet ($y = 0$ in local coordinates) to a point 400 mm from the center of the magnet along the direction of the particle beam when the gap and cross-over coils are excited to a current density of 409 A mm⁻² and the shield coils are excited to a current density of 220 A mm⁻². The induction plots $y = 0$ to 400 mm in the range of $x = \pm 30$ mm in the figure and are virtually indistinguishable from each other. The end field reverses just outside magnet. When the central induction is 6.542 T, the integrated induction from -400 mm to +400 mm is 2.6361 Tm. The integrated induction error is 7 parts in 10000 at ± 30 mm across the pole.

Figure 5 shows the magnetic induction from $y = 0$ to 400 mm from the center of the magnet, when the gap and cross-over coil current density is 82 A mm⁻² and the shield coil current density is -4 A mm⁻². The induction versus y from 0 to 400 mm in the range of $x = \pm 30$ mm are virtually indistinguishable from each other. The induction plot shown in Figure 5 shows a lower level of field reversal than is seen at full design central induction of 6.5 T. When the central induction is 1.408 T, the integrated induction from -400 mm to +400 mm is 0.5872 Tm. There is an error of 1.7 parts in 10000 over ± 30 mm across the pole. The integrated induction needed to bend a 300 MeV electron beam 30 degrees is 0.5239 Tm. To bend a 300 MeV electron beam the central induction of the magnet would be 1.2563 T.

V. CONCLUDING COMMENTS

The three dimensional field calculations show that the UCS baseline magnet will behave as a Vobly type dipole is supposed to behave. The full design field studies show that the field in the gap can be tuned by changing the shield coil current. A field uniformity of better than one part in 1000 was demonstrated over a width of 120 mm out of 180 mm of the cold pole width without iteration of the basic design. The field uniformity can be improved by changing the slope of the shield coil and by changing the location of the inner edge of the shield coil. These studies can be done during the engineering of the first prototype UCS dipole. At injection, the field in the dipole is even more uniform than it is at full field (0.02 percent over a width of 120 mm). Further engineering studies may permit one to reduce the pole width from 180 mm to 150 mm with a 25 percent reduction in the magnet mass.

At the full design induction of the magnet of 6.5 T, the peak magnetic induction in the coils is less than two percent higher than the central induction. (The peak induction in the coil is a little over 6.6 T.) The peak field in the winding occurs inside the end of the shield coil at the point where the

cross-over coil crosses the shield coil. Virtually everywhere else in the shield coil, the peak field is the central field. At the full design central induction, the iron in the return yoke at the magnet midplane is saturated with an induction in that region of about 2.5 T. The leakage flux at a point 180 mm from the magnet is less than one percent of the central induction. If leakage flux is an issue, one can increase the amount of iron in the magnet iron return path.

Even at high field, the magnetic induction along the direction of the beam behaves very much like a conventional copper iron dipole. The field falls off rapidly at the ends. The field drops from full field to near zero in about 1.5 gap length (60 mm). There is a small amount of field reversal about 50 mm from the end of the iron. The current in the cross-over coils contributes to the rapid field fall off at the ends of the magnet. The field generated by the baseline dipole is very uniform. Over a width of 60 mm the integrated field uniformity is better than 0.07 percent. Tracking studies show that 1.5 GeV electron beams 40 mm apart will bend to the same bending angle to 0.03 percent (0.16 milliradian in a bend of 0.524 radians).

The magnetic length of the baseline dipole at a central induction of 6.5 T is 403 mm about 27 mm longer than the iron pole. At a central induction of 1.4 T (near injection), the magnetic length of the 417 mm. The change in the magnetic from injection to full field is about 14 mm. It is not clear whether this a problem, because conventional magnets that have saturation in the poles will exhibit similar changes in magnetic length. Further study on this issue is needed.

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